

Engels, Stefan and Brauer, Achim and Buddelmeijer, Nico and Martín-Puertas, Celia and Rach, Oliver and Sachse, Dirk and van Geel, Bas (2016) Subdecadal-scale vegetation responses to a previously unknown late-Allerød climate fluctuation and Younger Dryas cooling at Lake Meerfelder Maar (Germany). *Journal of Quaternary Science*, 31 (7). pp. 741-752. ISSN 1099-1417

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Subdecadal-scale vegetation responses to a previously unknown late-Allerød climate fluctuation and Younger Dryas cooling at Lake Meerfelder Maar (Germany)

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Running title: a brief late-Allerød climate fluctuation at Lake Meerfelder Maar

Abstract

Lake Meerfelder Maar (MFM) is the northernmost W European sediment record with annual laminations across the Younger Dryas (YD), and the onset of the YD in the record of MFM has previously been defined as an increase in non-arboreal pollen abundance at ca 12,680 varve a BP. Here we present a palynological record at unprecedented subdecadal-resolution for MFM, covering the Allerød-YD transition. Our results show a fluctuation in pollen accumulation rates (PAR) prior to the onset of the YD, with lower PAR between ca 12,725 and 12,685 varve a BP. The fluctuation in PAR occurs simultaneous with a previously undescribed short fluctuation in sediment composition and varve thickness, as well as with changes in biogeochemical proxies. The combined evidence indicates signs of climatic instability ca. 45 years before the onset of the YD. The PAR records of *Betula* and *Pinus* furthermore show earlier and more abrupt changes at the onset of the YD than the percentage-records do. Finally, heliophilous herbaceous taxa show a delayed increase following the onset of the YD of ca. 145 years. This paper illustrates the potential to identify previously unrecognised climate variability and vegetation change when using subdecadal resolution analyses.

Keywords: Late-glacial; pollen accumulation rates; vegetation change; climate instability; Meerfelder Maar

Introduction

The onset of the Younger Dryas (YD) represents the last major cold period in the circum-Atlantic region (e.g. Goslar *et al.*, 1995; Björk *et al.*, 1996; Rasmussen *et al.*, 2006) and led to large-scale environmental changes on the European continent (e.g. Isarin *et al.*, 1998; Brauer *et al.*, 2008). Chironomid-based estimates of July air temperatures at the transition from the Allerød to the YD indicate a decrease of 3–4°C for W Europe (Heiri *et al.*, 2007; van Asch *et al.*, 2012; Brooks and Langdon, 2014), while other studies suggest that the onset of the YD was mainly characterised by a decrease in winter season temperatures (Lücke and Brauer, 2004; Denton *et al.*, 2005). In Greenland, the onset of Greenland Stadial-1 shows a centennial-scale decrease in $\delta^{18}\text{O}$ and the deuterium-excess record of the NGRIP ice core indicates an abrupt reorganization of the Arctic atmospheric circulation at this transition (Steffensen *et al.*, 2008).

Lake Meerfelder Maar (MFM), located in central-Western Europe (50°6'N, 6°45'E; Fig. 1), is the northernmost W European sediment record with annual laminations across the YD. The onset of the YD is defined by an increase in non-arboreal pollen (NAP) percentages and concurrent decreases in the abundance of *Betula* and *Pinus* pollen (Litt and Stebich, 1999; Litt *et al.*, 2003). The onset of the YD in the MFM records has been placed at the point of strongest change of NAP percentages between two adjacent pollen samples at 12,680 varve a BP (Litt and Stebich, 1999). An abrupt shift in micro-facies also occurred at ca 12,680 varve a BP. This major lithological change (Brauer *et al.*, 1999; Lücke and Brauer, 2004) coincided with the onset of the YD as observed in the palynological record, given the 30–40 year sampling resolution used by Brauer *et al.* (1999), Litt and Stebich (1999), and Lücke and Brauer (2004). The onset of the YD furthermore coincided with an abrupt and strong increase in varve thickness in the MFM record, interpreted to have resulted from a decrease in water depth as well as an increase in winter wind strength (Brauer *et al.*, 2008).

Rach *et al.* (2014) studied the hydrogen isotope values (δD) of lipid biomarkers extracted from the sediments of MFM in order to reconstruct palaeohydrological changes. They show that a stepwise decrease in biomarker δD values already started at 12,850 varve a BP, ca 170 years prior to the onset of the YD as defined by biostratigraphy. The results of Rach *et al.* (2014) indicate that climate change across the Allerød/YD-transition in W Europe does not represent a simple shift in temperatures but that it is composed of a complex succession of climatic and ecosystem changes, including shifts in temperature and evapotranspiration, as well as in

precipitation and wind regimes. The most prominent of these shifts was the one at ca 12,680 varve a BP, which coincides with the onset of the YD as defined by the increase in NAP-percentages and the change in micro-facies in the MFM record. These climatic changes likely had a range of different impacts on the physical environment and the vegetation, and, therefore, on the pollen assemblages.

Palynological records with a subdecadal to decadal resolution can reveal complex and dynamic changes in pollen percentage assemblages and pollen accumulation rates (PAR) in response to abrupt changes in environmental conditions during the Late-glacial (e.g. Ralska-Jasiewiczowa *et al.*, 2003; Ammann *et al.*, 2013). Lotter *et al.* (1992) identified the occurrence of two centennial-scale climate oscillations in the Swiss Alps during the Bølling/Allerød interstadial, termed the Aegelsee fluctuation during the earlier part of the interstadial and the Gerzensee fluctuation towards the end of the Allerød. The Aegelsee fluctuation was expressed as a change in both oxygen-isotope ratios as well as in the palynological records (as an increase in NAP), whereas the Gerzensee fluctuation could initially only be observed in the oxygen-isotope data presented in Lotter *et al.* (1992). Ammann *et al.* (2000) applied high-resolution multi-proxy analyses (including stable isotope and pollen analysis) to the Late-glacial record of Lake Gerzensee. Their results showed that although palynological evidence of a vegetational response to the minor climatic change associated with the Gerzensee fluctuation is not conspicuous, there is a statistically significant change in the palynological record just after the onset of the isotopic oscillation corresponding to the Gerzensee oscillation (Ammann *et al.*, 2000). Furthermore, the chironomid and cladocera records presented by Ammann *et al.* (2000) also show variation around the isotopic oscillation associated with the Gerzensee oscillation. Ammann *et al.* (2013) re-analysed the Late-glacial record of Lake Gerzensee (Switzerland), previously studied by Lotter *et al.* (1992). Amman *et al.* (2013) used a subdecadal-scale sampling resolution and their new palynological results provided more detail of the sequence of events during the climate transitions into and out of the YD, especially when focussing on the response time of vegetation to changes in climate.

Litt and Stebich (1999), Litt *et al.* (2003) and Brauer *et al.* (1999) describe a decadal-scale palynological record for the Late-glacial period of MFM. However, the relatively low sedimentation rate of 0.2-0.3 mm/a in the late Allerød (when compared to the sedimentation rates during the YD) and the 1-cm-thick samples investigated by Litt and Stebich (1999) resulted in a

~30-40 year sampling-resolution in the late Allerød, preventing the detection of decadal-scale fluctuations in vegetation.

Here we present the first palynological record for MFM with a subdecadal resolution covering the Allerød-YD transition with a special focus on the last 400 years before this major environmental shift. Our increased sampling resolution allows the detection of short-term variability, even during the late Allerød, which in the MFM record is characterized by a relatively low sedimentation rate. The main research aim of the present study is to improve on the current paradigm that the vegetation shift at the Allerød/YD-transition occurred as a simple shift in the AP/NAP-ratio by analysing the well-dated sequence of MFM in more detail. We will compare changes in vegetation to lithological (Brauer *et al.*, 1999; 2008), high-resolution element composition (this study) and biogeochemical (Rach *et al.*, 2014) shifts in the MFM sediment record.

Materials and methods

Sediment record and chronology

We analysed sediment cores that were retrieved from the deepest part of MFM using a UWITEC piston corer during fieldwork in 2009 (Martín-Puertas *et al.*, 2012; Rach *et al.*, 2014). Core sequences MFM09-A and -D were combined to form the MFM09 composite profile (Martín-Puertas *et al.*, 2012; Rach *et al.*, 2014), which has been matched with the older MFM-6 composite profile using microscopically defined marker layers. The MFM chronology is based on varve counting and varve thickness measurements on 10-cm-long thin sections of the MFM-6 profile using a petrographic microscope (Brauer *et al.*, 1999; Lane *et al.*, 2015).

The varve chronology for the interval above the Laacher See Tephra (LST) is identical to the previously published one (Brauer *et al.*, 1999), while for the part below the LST a revised version has been established (MFM-2015 chronology; Lane *et al.*, 2015), which, however, in the interval shown here does not differ from the previous MFM-6 chronology (Brauer *et al.*, 1999). The chronological anchor point is the LST dated at $12,880 \pm 40$ varve a BP, which is within uncertainties in agreement with the modelled age estimate of $12,937 \pm 23$ cal a BP of Bronk Ramsey *et al.* (2014). All ages in this paper are given as numbers that are rounded to the nearest multitude of 5. The uncertainty of ± 40 varve a is not repeated every time for better readability.

Palynological analysis

We significantly increased the sampling resolution compared to previous pollen analyses of Late-glacial sediments from MFM (Litt and Stebich, 1999), using 3-mm-thick samples for the late Allerød interval, and 5-mm-thick samples for the early YD. SI Table 1 provides details of the obtained samples and their ages. The difference in sampling resolution within our record follows the increase in varve thickness at the onset of the YD. We analysed 94 samples across the Allerød-YD transition interval (ca 13,060-12,480 varve a BP) with a subdecadal sampling resolution for 80% of our palynological samples. The samples were obtained by first pressing transparent L-shaped containers into an opened core-half (cores MFM09-D4 and -A5, where the 5-cm-thick Laacher See Tephra deposit was used as the boundary) in the laboratory. Marker layers were indicated on the container and pins were used to demark 1-cm intervals prior to sampling the L-shaped container using standard laboratory equipment (knives, forceps). Samples were immediately transferred to glass vials for processing and prepared following the techniques described in Faegri and Iversen (1989) and Moore *et al.* (1991). The samples were first boiled in KOH (10%) and subsequently in HCl (10%) and sieved over a 212 µm mesh. After washing and centrifuging the samples were dehydrated using 96% acetic acid and subsequently treated with an acetolysis mixture for 10 minutes. After cooling the samples were washed repetitively, and organic material was separated from the clastic material by heavy liquid separation using a bromoform-alcohol mixture. Routine checks of the heavy fraction did not reveal any selective loss of pollen during the separation process. A *Lycopodium*-tablet was added to the samples in order to enable the calculation of pollen concentrations and pollen accumulation rates (Stockmarr, 1971). A pollen-percentage diagram (Fig. 2) was calculated using a pollen sum ($n_{\text{average}}=290$) that included pollen of trees, shrubs and upland herbs, and the diagram was plotted using TILIA v 1.7.16 (Grimm, 2004). A pollen diagram with percent-abundances plotted against core depth is provided in the Supplementary Information (SI Figure 1); a diagram showing pollen-concentrations against varve age is provided as well (SI Figure 2).

PARs were calculated for each pollen taxon by first multiplying the number of encountered pollen by the ratio of the number of added *Lycopodium* spores and the number of spores encountered during analysis. This number was then divided by the known surface of each sample (3.6 cm² for the samples below the LST, and 5.0 cm² for the samples above the LST) and the number of varves included in each sample (range: 5-13 varves per sample; Supplementary

Table 1). A PAR diagram (Fig. 3) showing the number of palynomorphs/cm²/a was constructed in C2 (Juggins, 2003).

Numerical analysis

Zonation of the pollen diagram was carried out using the constrained hierarchical clustering method (Grimm, 1987) as included in the rioja-library (Juggins, 2015) in the R environment. We used the percent-abundance data set in our analysis, only including the taxa that are included in the pollen sum. We used a broken stick model (Bennett, 1996) to assess the significant number of zones, and we plot our results alongside the regional zonation for the Eifel as published by Litt and Stebich (1999).

We estimated the amount of palynological compositional change ('turnover') following the methods presented by Birks and Birks (2008). We ran a Detrended Canonical Correspondence Analysis (DCCA) using sample age as the only constraining variable on the square-root transformed percentage data of all the taxa included in the pollen sum, without down-weighting of rare taxa, with detrending by segments and with non-linear scaling using CANOCO v4.56 (ter Braak and Šmilauer, 2002) to obtain results that are comparable to those presented in Birks and Birks (2008). The sample scores (scaled in standard deviation (SD) units of compositional change or turnover with time) are interpreted to represent the beta-diversity or between-habitat diversity (Birks, 2007; Odgaard 2007; Birks and Birks, 2008). We repeated our analysis with a palynological datasheet where we obtained equally spaced time intervals (of 10 varve years) by linearly interpolating the pollen percentage data. As the results of this time-standardized analysis are very similar to the results obtained on the unstandardized dataset, we only present the latter in Fig. 2.

Elemental analysis

The element composition of the sediments was analysed non-destructively every 0.2 mm on the composite profile MFM-09 using an ITRAX X-ray fluorescence (XRF) core scanner at GFZ-Potsdam, Germany. The XRF core scanner irradiated the split core surface with a Mo X-ray source during 20 s, operated at 30 kV and 40 mA, generating energy dispersive fluorescence radiation. The element intensities of Si, K, Ca, Ti, Mn, Fe, Ni, Rb, Sr and Zr as well as relative

variations of the coherent and incoherent radiation were acquired non-destructively. The acquired chemical composition of the sediment is expressed as elements intensities (cps).

Results

Palynological analysis

Four statistically significant pollen zones have been identified in our percent-abundance data (Fig. 2). The pollen-spectra of zone PZ-1 (ca 13,060-12,750 varve a BP) were dominated by *Betula* and *Pinus*. The increase of *Pinus* from values of ca. 20% during PZ-1 to values over 40% most likely indicates the local expansion of pine during PZ-2 (ca 12,750-12,690 varve a BP). The late Allerød vegetation (PZ-1 and -2) around MFM therefore most likely consisted of birch-pine woodlands (Fig. 2). Relatively low percent-abundances of heliophilous herbs such as *Artemisia* indicate that some open habitats were present in a predominantly forested landscape (Litt and Stebich, 1999). Our new high-resolution pollen data show clear evidence for the effects of the Laacher See Eruption (LSE) (12,880 varve a BP) on the local vegetation. The birch-pine woodlands surrounding MFM underwent a reorganization of the vegetation following the LSE as pine temporarily disappeared from the region. A rapid succession of grassland to birch to birch-pine woodlands took place in the first 150 varve years after the LSE. A detailed analysis of the effects of the LSE on the vegetation around MFM and beyond is presented in Engels *et al.* (2015). For a more detailed description of the general vegetation development during the Allerød/YD period in the Eifel region we refer to Litt and Stebich (1999). Below, we focus on previously unrecognized features of vegetation change visible in our high-resolution record.

A major decrease in the AP/NAP ratio from 46% to 27% occurs between 12,695 and 12,675 varve a BP (Fig. 2; Fig. 4), reflecting the transition from the late Allerød to the YD. Our numerical analysis places the zone boundary (PZ-2 to PZ-3) that marks the onset of the YD in our new high-resolution record at 12,690 varve a BP. This is a decade earlier than the published onset of the YD by Litt and Stebich (1999) and this difference likely is the result of different sampling resolution. We comply with the published date for the definition of the onset of the Younger Dryas because the age difference of only 10 years falls within the dating uncertainty, and we use the conventional date of 12,680 varve a BP (Litt and Stebich, 1999) for the definition of the onset of the Younger Dryas in the remainder of this manuscript.

High percent-abundances of e.g. Poaceae, Cyperaceae and *Equisetum* are characteristic for PZ-3 (ca 12,690-12,545 varve a BP). The final transition that can be seen in our percentage record is observed at the onset of PZ-4 (12,545-12,480 varve a BP) which is characterised by an increase in abundances of *Artemisia* and *Rumex acetosella*-type and a decrease in pollen of *Betula*.

A DCCA with sample age as the sole constraining variable indicates that there is almost no compositional turnover visible during the late Allerød interval of our record. The exception is formed by a decrease of 0.4 SD units around the time of the Laacher See eruption (Fig. 2), which is followed by an increase to pre-disturbance values within a few decades. A second decrease in turnover can be seen at the Allerød-YD transition, after which the compositional turnover shows a nearly linear change throughout the remainder of our record.

PAR of the most abundant taxa (Fig. 3) show a distinct decline that already starts between ca 12,730 and 12,720 varve a BP, several decades prior to the onset of the YD (12,680 varve a BP). The total PAR of herbaceous taxa decreases from 500-1000 pollen/cm²/a prior to ca 12,725 varve a BP, to a minimum of ~175 pollen/cm²/a at 12,710 varve a BP, and recovers to pre-disturbance values by ca 12,685 varve a BP. This trend can be observed for the curves of most of the individual herbaceous taxa as well (e.g. Cyperaceae, Poaceae), but there are a few herbaceous taxa that show more or less stable PAR values throughout the interval 12,800-12,685 varve a BP (e.g. Asteraceae tubuliflorae). *Artemisia* and Apiaceae show a decrease in PAR that starts ca 15 varve years later than the general decrease in PAR as observed for most of the herbaceous taxa. Supplementary Fig. 2 shows the concentrations of the same taxa that are presented in Fig. 3 and shows a decrease in pollen concentrations that also occurs between ca 12,730 and 12,720 varve a BP and a recovery by ca 12,685 varve a BP for most but not all taxa.

Betula and *Pinus* PAR also decrease at ca 12,725 varve a BP, but they do not show a recovery similar to the herbaceous taxa. *Betula* shows a decrease from 1000-2000 pollen/cm²/a, prior to ca 12,725 varve a BP, to 250-400 pollen/cm²/a between ca 12,720 and 12,670 varve a BP, and a second decrease to values of 90-250 pollen/cm²/a at ca 12,665 varve a BP. *Pinus* decreases from a maximum PAR of ~1500 pollen/cm²/a at ca 12,730 varve a BP to values of 200-600 pollen/cm²/a until 12,480 varve a BP, which is the end of the studied interval. These trends differ from those observed for most herbaceous taxa: the recovery of the arboreal taxa at

12,685 varve a BP does not lead to PAR that are as high as before the decadal-scale decrease at 12,725 varve a BP, whereas most herbaceous taxa do show similar PAR before and after the decadal-scale decrease. Heliophilous herbs such as *Artemisia* and *Rumex acetosella*-type only reach maximum percent-abundances and PAR-numbers at around 12,535 varve a BP, some 145 varve years after the onset of the YD.

Micro-facies analysis and element composition

The major shift in varve micro-facies from siderite varves in the late Allerød to diatom-clastic varves in the YD has been previously described in detail by Brauer *et al.* (1999) and Lücke and Brauer (2004), who state that the increase in varve thickness at the onset of the YD is due to (1) massive diatom blooms (interpreted as caused by nutrient remobilisation due to increased water circulation) and (2) re-deposition of littoral sediments due to wave activity on the shorelines combined with a lake water level decline.

Here, we report a previously undescribed brief fluctuation in varve micro-facies during the late Allerød, lasting for only 11 varve years at ca. 12,720 varve a BP (Fig. 4), and occurring ca 40 varve years before the main shift in varve micro-facies at the onset of the YD (12,680 varve a BP; Brauer *et al.*, 2008). This short interval is characterized by an increase in mean varve thickness from ~0.2-0.3 mm to ~0.4-0.6 mm (Fig. 5) mainly caused by thicker organic sub-layers that contain higher abundances of small diatoms frustules (spring/summer). Similar to the facies change at the onset of the YD, siderite sub-layers vanish almost completely as the result of deeper lake-water circulation that increased oxygen availability in the deep water. Some of the layers contain biochemically precipitated calcite (Fig. 6). Typically, in mid-latitude lakes calcite forms in the epilimnion triggered by CO₂ consumption during spring and early summer algal blooms (Kelts and Hsü, 1978). In MFM this is a rarely observed process because there are no carbonate rocks outcropping in the catchment. Nevertheless, calcite precipitation in this interval is confirmed by thin section analyses and coincides with an increase in the occurrence of diatom frustules in these varves. Therefore, we interpret the formation of these varves as a short period of increased water circulation which, however, was less intense and, as a result, not as long-lasting as the increased circulation observed at the onset of the YD.

Changes in the element composition of the sediments agree with the observed micro-facies changes. Due to the predominantly basaltic composition of the MFM catchment (Irion &

Negendank, 1984), we consider Titanium (Ti) a suitable indicator for the clastic component of the sediment. Variations of the thickness of the siderite layers as inferred from microfacies analyses correspond well to relative changes in the detrital-normalized iron represented here by $\ln(\text{Fe}/\text{Ti})$ ratios (Brauer *et al.*, 2008). The Allerød-YD transition is characterized by an increase in detrital input (higher Ti values) and lower $\ln(\text{Fe}/\text{Ti})$ ratios as a consequence of reduced authigenic iron-minerals precipitation (siderite varves) (Fig. 4). Similar changes, but at much lower amplitude, are observed between ca 12,725 and 12,715 varve a BP corresponding to the brief fluctuation described above (Fig. 5). The LST at 12,880 varve a BP is characterized by the highest Ti values (Fig. 4). The 15-year-long Ti peak preceding and following the air-fall ash deposit reflects ash material that penetrated into the underlying sediments corresponding to the five years before the volcanic eruption as well as reworked ash material during the first decade after the eruption (Fig. 4).

Discussion

Identification of a previously unrecognised decadal-scale climate oscillation prior to the onset of the YD

Our PAR data show that values of *Betula*, *Pinus* and most of the herbs show a distinct fluctuation starting at ca 12,725 varve a BP (Fig. 4c), ~55 years before the onset of the YD (Litt and Stebich, 1999). This decrease in PAR was not previously observed at MFM, nor is it evident in other palynological records with a high sampling resolution (e.g. Wick, 2000; Ammann *et al.*, 2013). It also does not coincide with to the so-called Gerzensee oscillation (e.g. Lotter *et al.*, 1992), which ended shortly after the Laacher See eruption, ca 150 years earlier than the oscillation we observe in our record.

The PAR-decrease that we observe in our record could have been the result of decreased pollen production under less favourable climatic conditions, such as a decrease in temperature, which has been suggested to have started as early as 12,850 varve a BP based on lipid biomarker δD data (Rach *et al.*, 2014; Fig 4e). Notably, the decrease in δD values of the higher plant-derived $n\text{C}_{29}$ *n*-alkane (most likely derived from *Betula*, with possible contributions from *Salix* and *Poaceae*) from ca. -189‰ to -205 ‰ between 12,750 and 12,710 varve a BP was coincident with the decrease in PAR values. Rach *et al.* (2014) interpret the decrease in δD as an indication

of regional cooling in western Europe combined with a change in δD values of North Atlantic surface waters.

The varve thickness record and the element composition of the sediments also show evidence for the presence of a shorter oscillation occurring before the onset of the YD. Minor time lags at the onset of the oscillation and differences in the duration of the response observed between palynological and micro-facies data can be the result of different proxy-sensitivity to the relatively weak forcing that might have driven the observed changes. Annual layer counting reveals a fluctuation of 11 varve years at ca 12,725-12,715 varve a BP that was characterised by relatively thicker varves (Fig. 4d). This increase in varve thickness is due to the sudden appearance of discrete diatom sub-layers and a slight increase in the minerogenic input into the lake (relatively higher Ti values). The intensification of diatom bloom, together with an increase in reworked littoral sediment and the cessation of siderite formation in varves at the beginning of the YD was interpreted as an indicator of more intense water circulation that led to nutrient upwelling and increased lake productivity (Brauer *et al.*, 2008). In the case of the precursor fluctuation at 12,725-12,715 varve a BP, the reduced siderite precipitation and lower $\ln(\text{Fe}/\text{Ti})$ ratios (Fig. 4d), both indicative of less anoxic bottom water conditions, also support wind-induced deeper lake water circulation. Therefore the attenuated proxy response, compared to the onset of the YD, suggests a similar mechanism (increased wind activity) but with lower magnitude than at the onset of the YD. Moreover, unlike the long-lasting shift in the depositional system at the onset of the YD, this short period of change represents a true oscillation: siderite varves occur before the fluctuation and the same varve type (siderite varves) recurs after the fluctuation, and PAR decreases at the onset of the fluctuation, and increases again afterward. This further indicates that the driver of this short oscillation was less intense and/or of shorter duration than the one at the onset of the YD. We hypothesize a short-lasting, non-stable change in atmospheric circulation causing increased windiness as a possible driver for this fluctuation. To prove this hypothesis additional data from other sites in Europe are needed, providing better information about its spatio-temporal signature. Reconstructions of small-scale climate variability that may have preceded large climatic shifts such as the onset of the YD might provide vital clues to improve our understanding of potential drivers of climate change and ecosystem response. A strong chronological control as well as a very high sampling resolution is

needed to be able to identify climate instability such as the decadal-scale oscillation discussed here.

The definition of the Allerød-Younger Dryas transition: biostratigraphy and climate change

Many sedimentary records that are available for palaeoclimatologists and palaeoecologists lack the chronological control or the sedimentation rate that is needed to allow for the identification of (sub-) decadal-scale ecosystem and climate change. These records, however, do for example allow the reconstruction of spatial patterns of change on longer (centennial to millennial) timescales (e.g. Giesecke *et al.*, 2014), or of continental-scale changes in distribution patterns of specific taxa (e.g. Giesecke *et al.*, 2011). As such, palynological records that lack a (sub-)decadal sampling resolution are important for palaeoecological and palaeoclimatological reconstructions.

The continental-scale analysis of European vegetation change during the Holocene by Giesecke *et al.* (2011) shows that with a centennial-scale temporal resolution the expansion of e.g. *Corylus avellana* was broadly synchronous at far apart sites. However, high-resolution results by Ammann *et al.* (2013) and van Raden *et al.* (2013) suggest that changes in climate and especially the subsequent ecosystem responses might not be synchronous on a (sub-) decadal scale. Furthermore, while the mid-point of change is often easily defined and as such a robust tool to use in characterising e.g. biostratigraphical zones, high-resolution annually laminated records such as MFM indicate that the mid-point of change is not the best option to define the onset of climate change or the timing of ecosystem response to such changes. Only by high-resolution studies of time intervals representing climate change and by establishing detailed independent chronologies, avoiding ‘correlations’ through curve matching, can the differences in timing of the onset of climate change and the start of ecosystem response be identified and quantified (e.g. Björk *et al.*, 1998; Blockley *et al.*, 2012). A record such as MFM with its robust chronology and its availability of many high-resolution and high-quality proxy records (e.g. Martín-Puertas *et al.*, 2012; Rach *et al.*, 2014; Engels *et al.*, 2015) can play a key role in the process of better understanding leads and lags that may occur on a (sub-)decadal scale (Ammann *et al.*, 2000; 2013; Lane *et al.*, 2013; Wick 2000; this study). Our high-resolution record shows that previously unrecognised climate instability is evident in three independent proxy records (i.e. palynology, sedimentology and biogeochemistry), several decades before the Allerød-YD transition. Small-scale differences observed in these proxy records suggest that individual

climate-proxy records are not synchronous in their initial reactions (passing thresholds at different moments), which is likely the effect of (a) sampling resolution and (b) proxy-sensitivity.

Difference in trends of percent-abundance curves and PAR curves

The lithological record of MFM showed an abrupt change in varve thickness and a major shift in micro-facies from one year to the next at 12,680 varve a BP (Brauer *et al.*, 2008). Percent-abundances of *Pinus* showed a decrease of 20% within a 20-year period (Fig. 4b) across this transition. *Pinus* pollen that is persistently present after that date and throughout the YD might mainly represent long-distance transported pollen, as increased windiness (Brauer *et al.*, 2008) may have favoured the accumulation of allochthonous (long-distance transported) pollen. The percent-abundance diagram suggests that *Betula* showed a more gradual response to decreasing temperatures across the transition into the YD than *Pinus*, as percent-abundances of *Betula* started to decrease already as early as at 12,710 varve a BP. Compositional turnover (Fig. 2), calculated using the percentage-data, shows its strongest decrease just after 12,680 varve a BP.

PAR of both *Pinus* and *Betula* however already decrease at ca 12,725 varve a BP, which is ~35 and ~15 years before the decreases in percent-abundances of *Pinus* and *Betula*, respectively. The difference in timing of the decrease in percent-abundance of *Pinus* and *Betula* therefore does not seem to reflect the vegetation development in the area around MFM, but seems to result from the different ability of the remnant vegetation to produce pollen under cooling climate conditions. The decrease in percent-abundances of *Betula* (from 31% to 19% between 12,675 and 12,670 varve a BP) just after the onset of the YD might reflect a change in the vegetation, as PAR of *Betula* decrease from 350 to 220 pollen/cm²/a at this time as well.

Theuerkauf and Joosten (2012) present PAR values for a high number of sites in Germany that span (part of) the YD. Reconstructed PAR values for the YD at MFM are similar to the results by Theuerkauf and Joosten (2012) for many of the common taxa, including *Betula*, *Artemisia* and Poaceae. The PAR values of *Pinus* presented by Theuerkauf and Joosten (2012) for their southernmost sites are between 6000 and 10,000 grains/cm²/a, which is an order of magnitude higher than the values obtained for *Pinus* in the present study (200-400 grains/cm²/a during the YD). The low values that are observed at MFM however do corroborate the results of

Theuerkauf and Joosten (2012) which show a strong east-to-west gradient in *Pinus* pollen abundance across Europe during the YD.

These results illustrate the advantages of calculating pollen accumulation rates when analysing short-term changes in palynological results, as the decrease in pollen production around 12,725 varve a BP is not reflected in the percentage diagram. However, detailed chronological information is needed to enable the distinction between fluctuations that might be due to short term fluctuations in sedimentation rates (which might not be visible in non-laminated sediments) from real fluctuations in PAR.

Delayed increase in heliophilous herbaceous taxa following the onset of the Younger Dryas

Several taxa that are typically considered to be pioneer taxa with a preference for open, mineral soils (Birks, 1986) take a long time to increase in PAR after the onset of the YD. For instance, *Artemisia* and *Rumex acetosella*-type take ca. 145 varve years before reaching their maximum pollen-abundances after the onset of the YD (Fig. 4), and a statistically significant transition in the pollen percentage data of these taxa is identified at 12,545 varve a BP (PZ-3 to PZ-4 boundary).

The delayed increase in pollen percentages and PAR might have been an effect of the (partly dead) trees and thermophilous herbaceous taxa that were still present in the landscape around MFM as relicts of the Allerød vegetation. Habitats for heliophilous pioneer plant communities might have only become available after the disappearance of the relict vegetation and the development of open, mineral soils. A similar observation has been made in the sub-decadal pollen record from Lake Gerzensee (Switzerland), which exhibits a ~100 year delay in the increase of percent-abundances of e.g. *Artemisia* after the onset of the YD (Ammann *et al.*, 2013). This supports our interpretation of a competition effect across the Allerød-YD transition as an explanation for the delayed increase of heliophilous herbaceous taxa.

Conclusions

We used a subdecadal-resolution palynological record retrieved from the annually laminated sediment record of Lake Meerfelder Maar to test the current paradigm that the vegetation shift at the onset of the YD was expressed as a multi-decadal shift in the AP/NAP-ratio. Our new high-resolution data show that pollen accumulation rates decreased between ca 12,725 and 12,685

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varve a BP. This previously unobserved 40-year-long fluctuation occurs several decades before the onset of the YD as defined by biostratigraphy (sensu Litt *et al.* 2003). The decrease in PAR coincides with an increase of varve thickness and a change in micro-facies between 12,720 and 12,710 varve a BP, as well as with a decrease in the δD values of the higher plant-derived nC_{29} n -alkane. Together, these records provide evidence for the occurrence of a previously unknown decadal-scale climate fluctuation during the late Allerød.

Our results furthermore show a difference in timing between the percent-abundance curves and the PAR-curves of the most important taxa (i.e. *Betula*, *Pinus*). This suggests that although biostratigraphy remains a useful tool for upscaling individual proxy-records to regional patterns of change, high-resolution proxy analyses on well-dated records provide a means to additionally decipher even (sub-)decadal ecosystem and climate change. Finally, our records indicate a delayed increase in heliophilous taxa after the onset of the YD. This delay of ca. 145 varve years might be the result of time-demanding competition effects with plant species that were components of the vegetation during the late Allerød period.

This study illustrates the potential to identify small-scale and low-amplitude climate variability when using ultra-high-scale resolution analyses on suitable records such as MFM. Our results show that subdecadal palaeoecological data can provide an improved understanding of the complex changes in climate and vegetation associated with the onset of the YD.

Acknowledgements

We thank Annemarie Philip (University of Amsterdam) for preparation of the pollen slides. This study is a contribution to the Helmholtz-Association climate initiative REKLIM (Topic 8 ‘Rapid Climate Change from Proxy Data’) and has used infrastructure of the Terrestrial Environmental Observatory (TERENO). We thank the Maar Museum in Manderscheid (www.maarmuseum.de/) for local support. We are grateful for the insightful suggestions and comments by reviewers Walter Finsinger and Thomas Giesecke that helped to improve this manuscript. The authors declare no conflicts of interest.

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Figure captions

Fig. 1: Map showing the location of Lake Meerfelder Maar (Germany)

Fig. 2: Pollen percentage diagram for the late Allerød- early Younger Dryas transition at Lake Meerfelder Maar. The samples are expressed as percentages of the total pollen sum, which includes pollen from trees, shrubs, Ericales and upland herbs and are plotted on a varve age-scale (varve a BP). The graph entitled 'Turnover' shows the estimated compositional turnover (β diversity) expressed as standard deviation (SD) units (cf. Birks & Birks, 2008; see text). The dashed line at 12,880 varve a BP marks the presence of the 6-cm-thick Laacher See Tephra (LST). The grey band marked (A) indicates the time interval of the formation of calcite-diatom varves (see text and Fig. 6). Pollen zones (PZ-x) show the statistically significant pollen-zones calculated using the data presented in this study. The regional zonation with the horizontal line at 12,679 varve a BP marks the onset of the YD as defined by Litt and Stebich (1999).

Fig. 3: Pollen accumulation rate (PAR) diagram for the late Allerød/Younger Dryas transition at Meerfelder Maar on a varve age scale (varve a BP). Selected taxa are shown in palynomorphs/cm²/a. Note the different x-scales used in the diagram. Zonation is based on the percentage-diagram: see Fig. 2 and text for more information.

Fig. 4: The Allerød-YD transition in Meerfelder Maar; a) Core description; b) Main pollen diagram and selected percent-abundance curves of arboreal taxa (dark green), non-arboreal taxa (beige) and *Equisetum* (blue) (%); c) PAR values of selected taxa (pollen/cm²/a) (the sample at 12,932 varve a BP has been removed for plotting purposes

as it showed extreme values, probably as a result of laboratory issues); d) Varve thickness (mm) record (Brauer *et al.*, 2008), normalized titanium (Ti) variability and element ratio $\ln(\text{Fe}/\text{Ti})$ determined using μ -XRF core scanner, all with a LOESS smoother; e) hydrogen isotope measurements (expressed as δD) on compound-specific lipid biomarkers; the blue line shows measurements on the $n\text{C}_{23}$ alkane likely derived from aquatic plants ($\delta\text{D}_{\text{aq}}$), the green line shows δD values of the $n\text{C}_{29}$ alkane, derived from higher terrestrial plants ($\delta\text{D}_{\text{terr}}$; Rach *et al.*, 2014). $\epsilon_{\text{terr-aq}}$ is the difference between $\delta\text{D}_{\text{terr}}$ and $\delta\text{D}_{\text{aq}}$ and interpreted to reflect terrestrial evapotranspiration (ETA; Rach *et al.*, 2014). The grey shading indicates the classical biostratigraphical zonation of Litt & Stebich (1999) based on the decrease in NAP and the change in lithology at 12,679 varve a BP (Brauer *et al.*, 2008), the dark band marked (A) indicates the time interval of the formation of calcite-diatom varves (see text and Fig. 6).

Fig. 5: Detail of the 12,800-12,600 varve a BP interval of the MFM record presented in this study; a) Main pollen diagram; b) PAR value of selected taxa; c) Sedimentological data. Zonation is based on the percentage-diagram: see Fig. 2 and text for more information. See caption of Fig. 4 for more details.

Fig. 6: Left: Thin section images (polarized light, flatbed scanner without microscopic magnification) showing late Allerød siderite (yellowish layers) varves and darker clastic-organic Younger Dryas varves. The indicated section (A) shows a short interval of endogenic calcite (whitish layers) and diatom-rich (dark layers) varves. Right: thin sections images (polarized light) of late Allerød siderite varves (upper image) and a detail of the short intercalated interval of calcite-diatom varves (lower image).



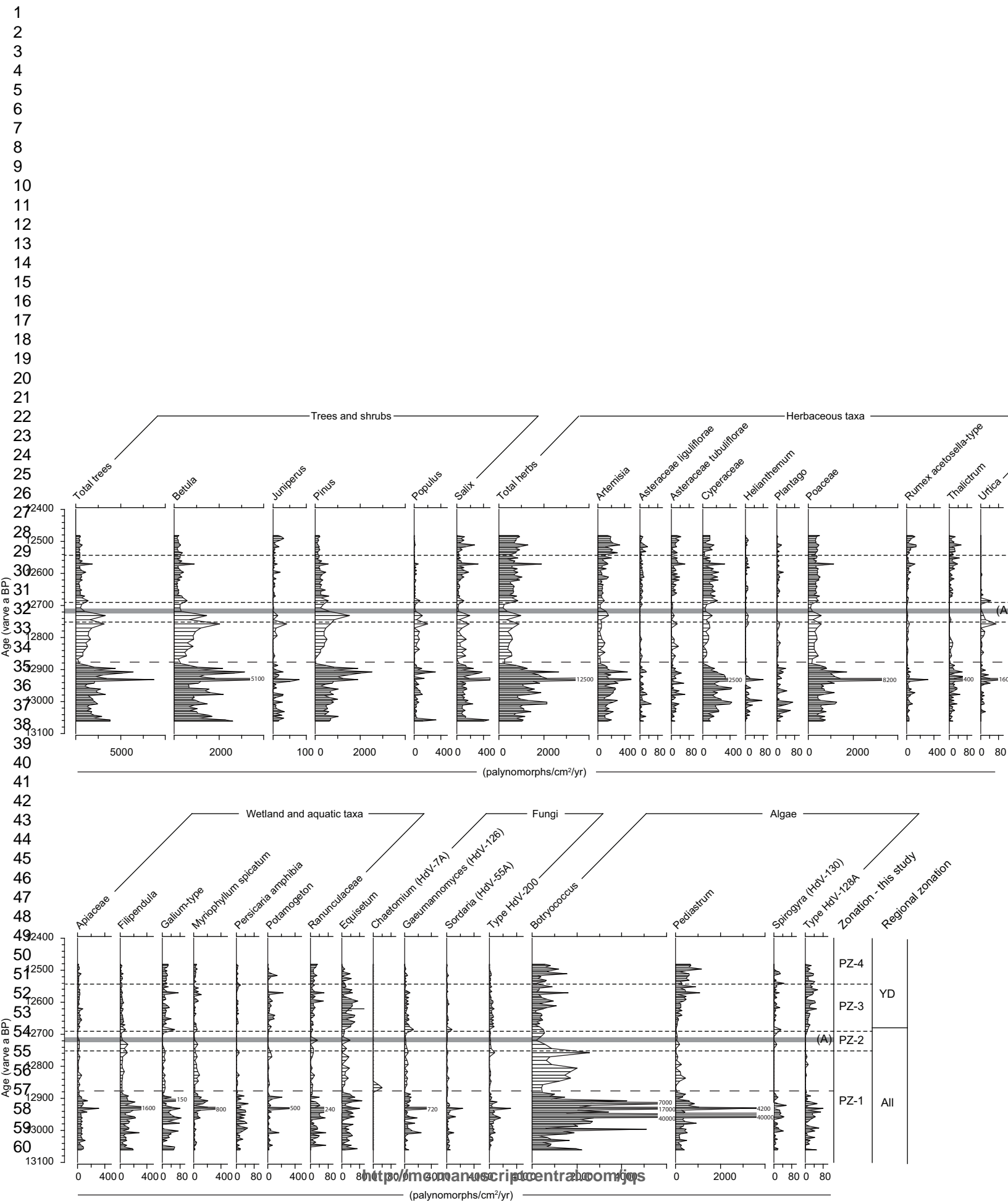
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FIGURE 1



Fig. 2

<http://mc.manuscriptcentral.com/jqs>



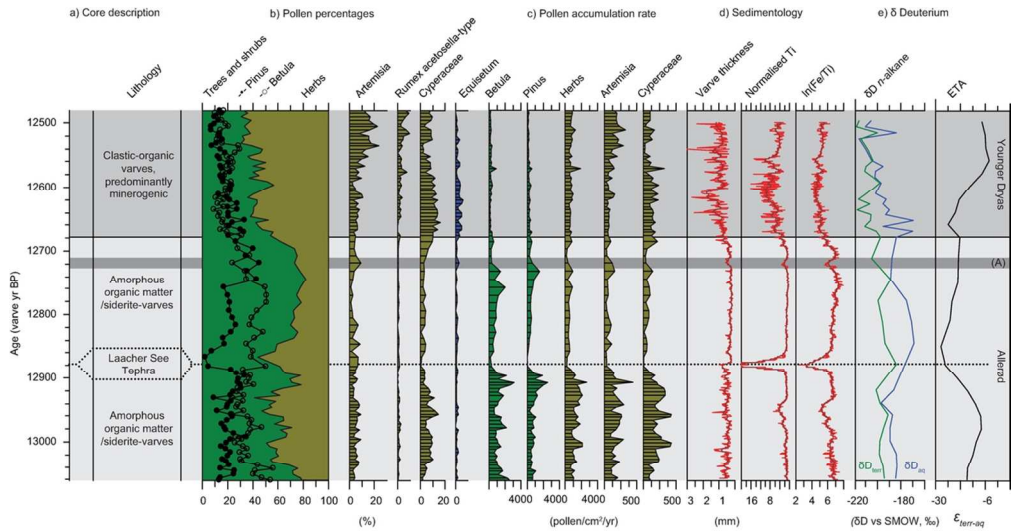


Fig. 4: The Allerød-YD transition in Meerfelder Maar; a) Core description; b) Main pollen diagram and selected percent-abundance curves of arboreal taxa (dark green), non-arboreal taxa (beige) and Equisetum (blue) (%); c) PAR values of selected taxa (pollen/cm²/a) (the sample at 12,932 varve a BP has been removed for plotting purposes as it showed extreme values, probably as a result of laboratory issues); d) Varve thickness (mm) record (Brauer et al., 2008), normalized titanium (Ti) variability and element ratio ln(Fe/Ti) determined using μ -XRF core scanner, all with a LOESS smoother; e) hydrogen isotope measurements (expressed as δ D) on compound-specific lipid biomarkers; the blue line shows measurements on the nC23 alkane likely derived from aquatic plants (δ D_{aq}), the green line shows δ D values of the nC29 alkane, derived from higher terrestrial plants (δ D_{terr}; Rach et al., 2014). $\epsilon_{terr-aq}$ is the difference between δ D_{terr} and δ D_{aq} and interpreted to reflect terrestrial evapotranspiration (ETA; Rach et al., 2014). The grey shading indicates the classical biostratigraphical zonation of Litt & Stebich (1999) based on the decrease in NAP and the change in lithology at 12,679 varve a BP (Brauer et al., 2008), the dark band marked (A) indicates the time interval of the formation of calcite-diatom varves (see text and Fig. 6).

Fig. 4

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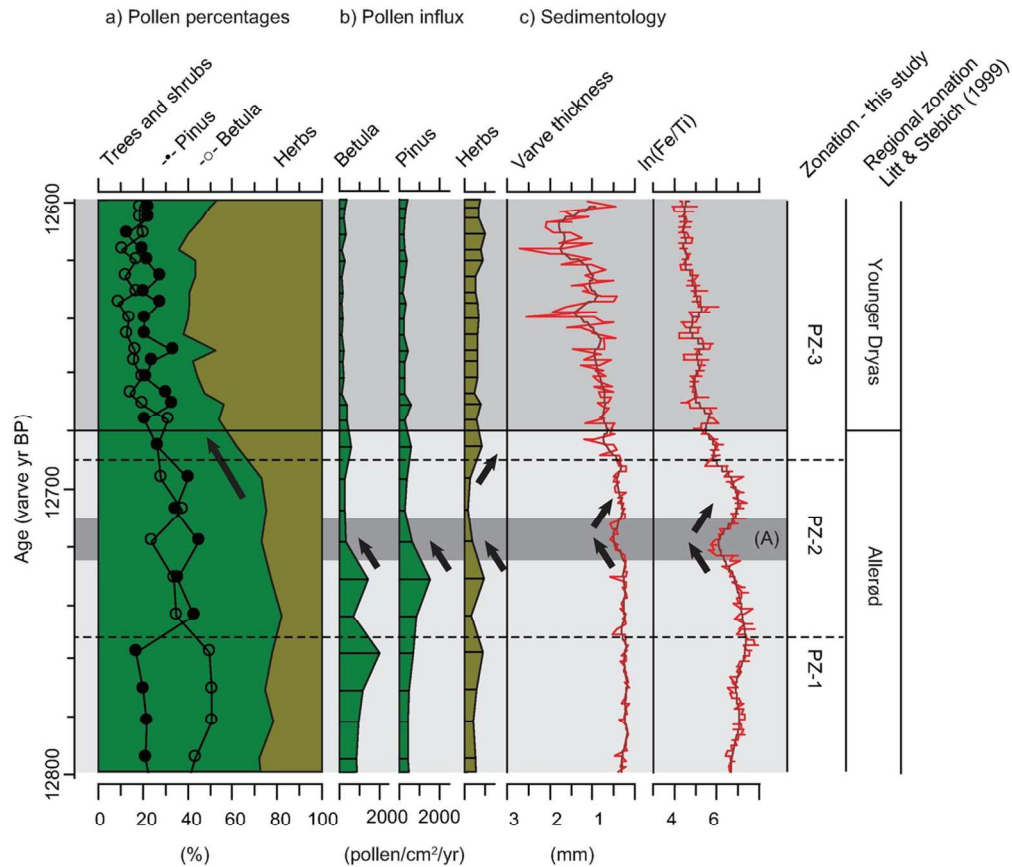


FIGURE 5

Fig. 5: Detail of the 12,800-12,600 varve a BP interval of the MFM record presented in this study; a) Main pollen diagram; b) PAR value of selected taxa; c) Sedimentological data. Zonation is based on the percentage-diagram: see Fig. 2 and text for more information. See caption of Fig. 4 for more details.

Fig. 5

102x93mm (300 x 300 DPI)

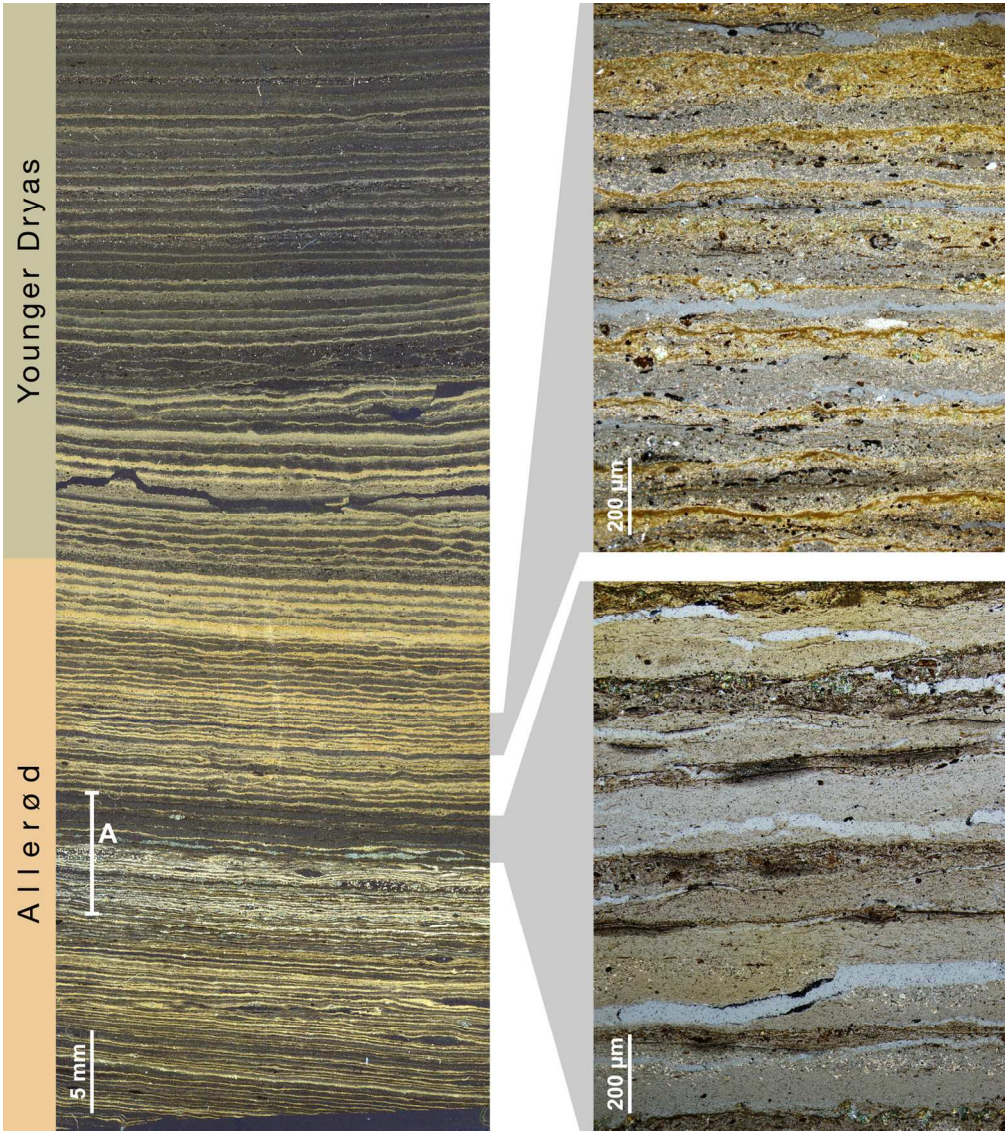


Fig. 6: Left: scanned thin section (polarized light, flatbed scanner without microscopic magnification) showing late Allerød siderite (yellowish layers) varves and darker clastic-organic Younger Dryas varves. The indicated section (A) shows a short interval of endogenic calcite (whitish layers) and diatom-rich (dark layers) varves. Right: thin sections images (polarized light) of late Allerød siderite varves (upper image) and a detail of the short intercalated interval of calcite-diatom varves (lower image).

Fig. 6
140x158mm (300 x 300 DPI)

Supplementary Information

Figure caption

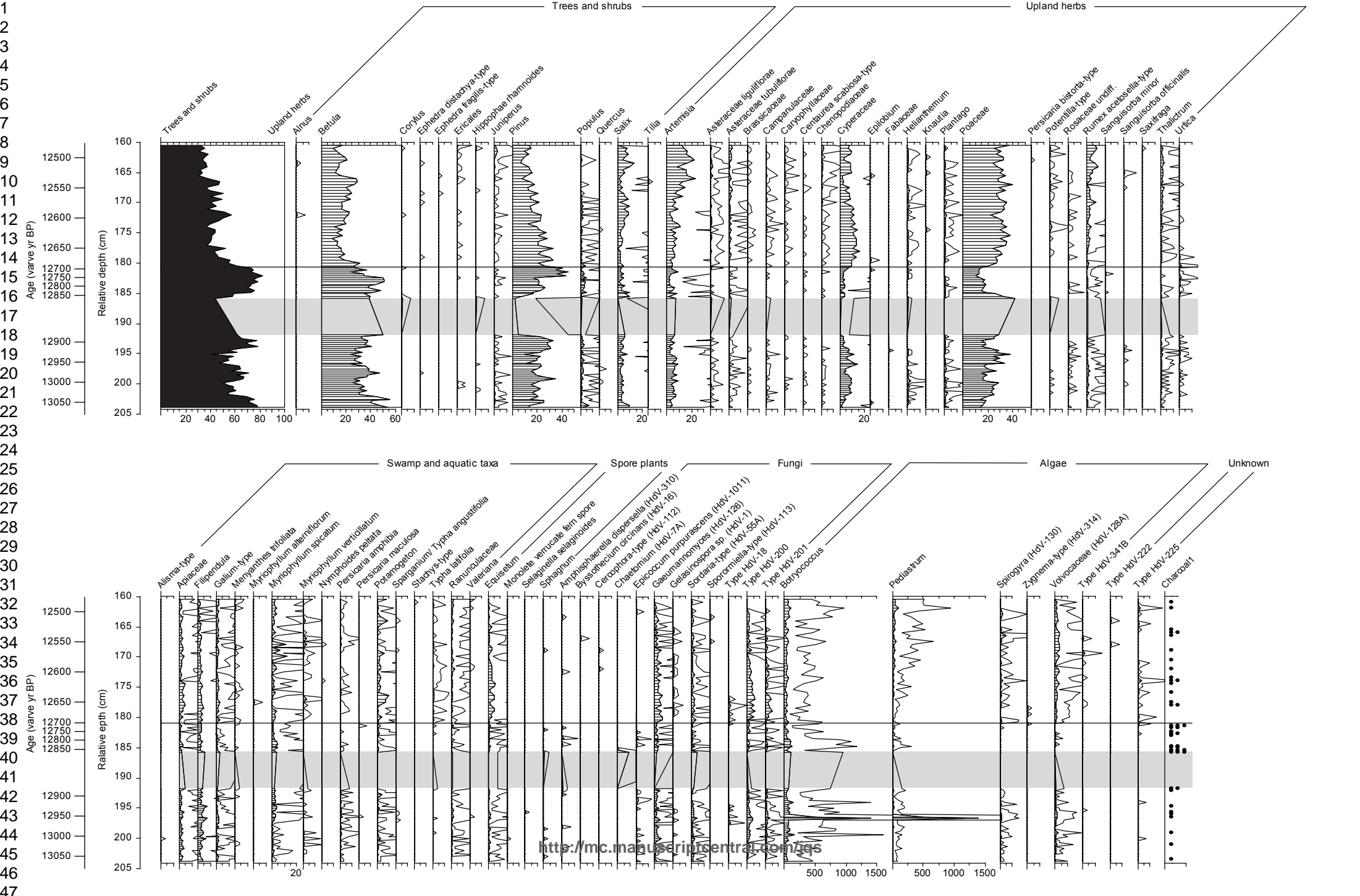
SI Figure 1: Pollen percentage diagram for the late Allerød- early Younger Dryas transition at Lake Meerfelder Maar plotted on a relative depth scale (cm). The samples are expressed as percentages of the total pollen sum, which includes pollen from trees, shrubs, Ericales and upland herbs and are plotted on a varve age-scale (varve a BP). The shaded area represents the presence of the 6-cm-thick Laacher See Tephra

SI Figure 2: Diagram showing concentration values (pollen/cm³) for selected taxa for the late Allerød/ Younger Dryas transition at Meerfelder Maar on a varve age scale (varve a BP). Note the different x-scales used in the diagram. The horizontal line at 12,679 varve a BP marks the onset of the YD as defined by Litt and Stebich (1999), the dashed line at 12,880 varve yr BP marks the presence of the 6-cm-thick Laacher See Tephra (LST). The sample at 12,932 varve a BP has been left out of the diagram for plotting purposes, as it showed extremely high values, most likely due to some atypical laboratory events (such as incomplete dissolving of the Lycopodium tablet)

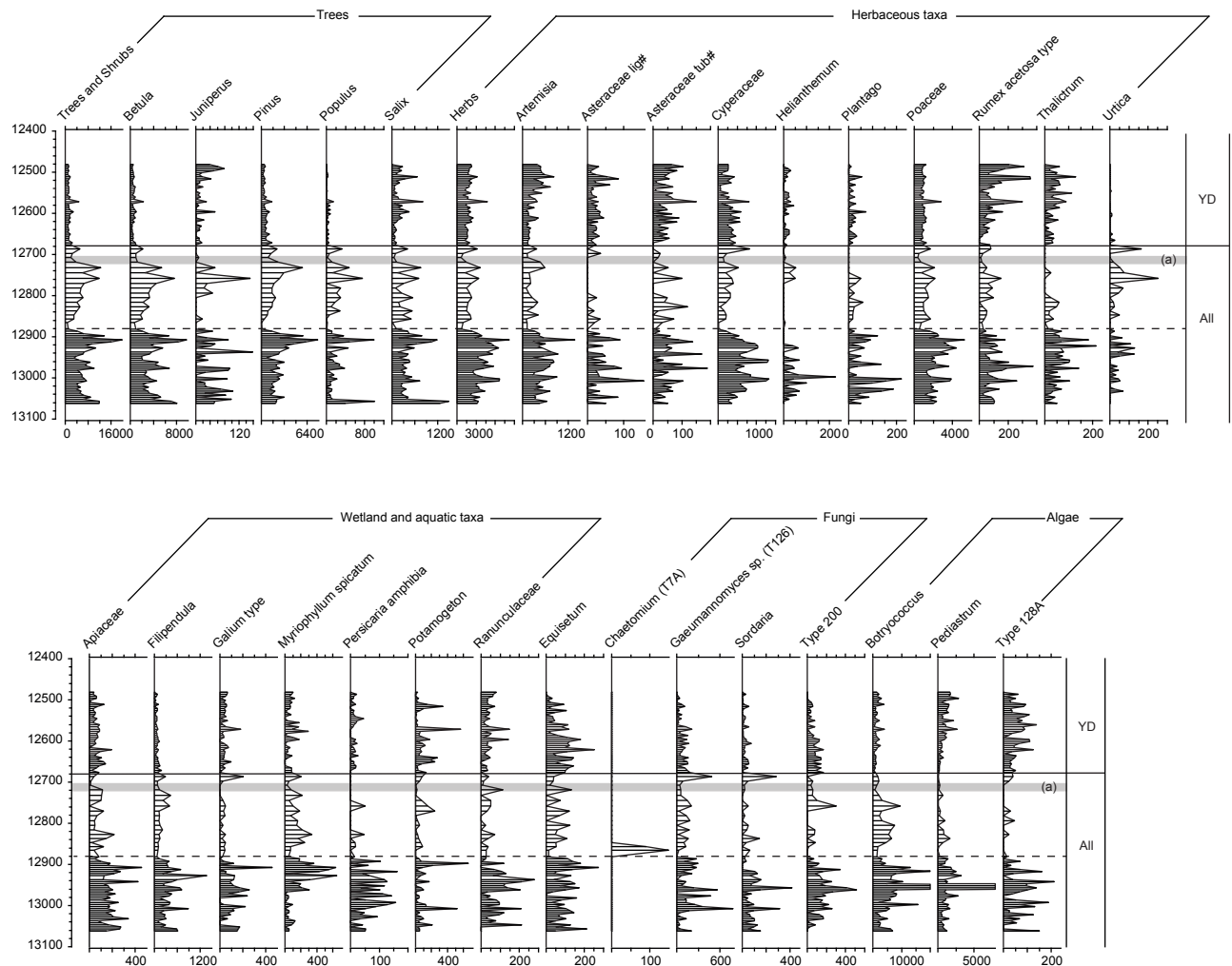
Table caption

SI Table 1: Varve chronology and sampling details of the Meerfelder Maar sequence presented in this manuscript. Relative depths are rounded to millimetres, varve ages are rounded to the nearest year.

Supplementary Fig. 1
Meerfelder Maar: Allerød-Younger Dryas transition



Supplementary Fig. 2



	Sample code	Core segment	Relative depth (Volume (cc)	#varves (yr)	Median age (varve yr)	
1							
2							
3	1	160.5	MFM09-D4	5	2.5	5	12481
4	2	161.0	MFM09-D4	10	2.5	5	12486
5							
6	3	161.5	MFM09-D4	15	2.5	5	12491
7	4	162.0	MFM09-D4	20	2.5	5	12496
8	5	162.5	MFM09-D4	25	2.5	5	12501
9	6	163.0	MFM09-D4	30	2.5	5	12506
10	7	163.5	MFM09-D4	35	2.5	5	12511
11	8	164.0	MFM09-D4	40	2.5	5	12516
12	9	164.5	MFM09-D4	45	2.5	5	12521
13							
14	10	165.0	MFM09-D4	50	2.5	5	12526
15	11	165.5	MFM09-D4	55	2.5	5	12531
16	12	166.0	MFM09-D4	60	2.5	5	12536
17	13	166.5	MFM09-D4	65	2.5	5	12541
18	14	167.0	MFM09-D4	70	2.5	5	12546
19	15	167.5	MFM09-D4	75	2.5	5	12551
20	16	168.0	MFM09-D4	80	2.5	5	12556
21	17	168.5	MFM09-D4	85	2.5	5	12561
22	18	169.0	MFM09-D4	90	2.5	5	12566
23	19	169.5	MFM09-D4	95	2.5	5	12571
24							
25	20	170.0	MFM09-D4	100	2.5	5	12576
26	21	170.5	MFM09-D4	105	2.5	5	12581
27	22	171.0	MFM09-D4	110	2.5	5	12586
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29	23	171.5	MFM09-D4	115	2.5	5	12591
30	24	172.0	MFM09-D4	120	2.5	5	12596
31	25	172.5	MFM09-D4	125	2.5	5	12601
32	26	173.0	MFM09-D4	130	2.5	5	12606
33	27	173.5	MFM09-D4	135	2.5	5	12611
34	28	174.0	MFM09-D4	140	2.5	5	12616
35	29	174.5	MFM09-D4	145	2.5	5	12621
36	30	175.0	MFM09-D4	150	2.5	5	12626
37	31	175.5	MFM09-D4	155	2.5	5	12631
38	32	176.0	MFM09-D4	160	2.5	5	12636
39	33	176.5	MFM09-D4	165	2.5	5	12641
40	34	177.0	MFM09-D4	170	2.5	5	12646
41	35	177.5	MFM09-D4	175	2.5	5	12651
42	36	178.0	MFM09-D4	180	2.5	5	12656
43	37	178.5	MFM09-D4	185	2.5	5	12661
44	38	179.0	MFM09-D4	190	2.5	5	12666
45	39	179.5	MFM09-D4	195	2.5	5	12671
46	40	180.0	MFM09-D4	200	2.5	10	12676
47	41	181a	MFM09-D4	205	1.33	11	12686
48	42	181b	MFM09-D4	208	1.33	11	12697
49	43	181c	MFM09-D4	211	1.33	11	12708
50	44	182a	MFM09-D4	215	1.33	13	12719
51	45	182b	MFM09-D4	218	1.33	13	12732
52	46	182c	MFM09-D4	221	1.33	13	12745
53	47	183a	MFM09-D4	225	1.33	12	12758
54	48	183b	MFM09-D4	228	1.33	12	12770
55	49	183c	MFM09-D4	231	1.33	12	12782
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2	50	184a	MFM09-D4	235	1.33	11	12794
3	51	184b	MFM09-D4	238	1.33	11	12805
4	52	184c	MFM09-D4	241	1.33	11	12816
5	53	185a	MFM09-D4	245	1.33	10	12827
6	54	185b	MFM09-D4	248	1.33	10	12837
7	55	185c	MFM09-D4	251	1.33	10	12847
8	56	186a	MFM09-D4	255	1.33	9	12857
9	57	186b	MFM09-D4	258	1.33	9	12866
10	58	186c	MFM09-D4	261	1.33	9	12875
11	59	LST		NA		1	12880
12	60	58b	MFM09-A5	318	1.17	5	12882
13	61	58c	MFM09-A5	321	1.17	5	12887
14	62	59a	MFM09-A5	325	1.17	5	12892
15	63	59b	MFM09-A5	328	1.17	5	12897
16	64	59c	MFM09-A5	331	1.17	5	12902
17	65	60a	MFM09-A5	335	1.17	5	12907
18	66	60b	MFM09-A5	338	1.17	5	12912
19	67	60c	MFM09-A5	341	1.17	5	12917
20	68	61a	MFM09-A5	345	1.17	5	12922
21	69	61b	MFM09-A5	348	1.17	5	12927
22	70	61c	MFM09-A5	351	1.17	5	12932
23	71	62a	MFM09-A5	355	1.17	5	12937
24	72	62b	MFM09-A5	358	1.17	5	12942
25	73	62c	MFM09-A5	361	1.17	5	12947
26	74	63a	MFM09-A5	365	1.17	5	12952
27	75	63b	MFM09-A5	368	1.17	5	12957
28	76	63c	MFM09-A5	371	1.17	5	12962
29	77	64a	MFM09-A5	375	1.17	5	12967
30	78	64b	MFM09-A5	378	1.17	5	12972
31	79	64c	MFM09-A5	381	1.17	5	12977
32	80	65a	MFM09-A5	385	1.17	5	12982
33	81	65b	MFM09-A5	388	1.17	5	12987
34	82	65c	MFM09-A5	391	1.17	5	12992
35	83	66a	MFM09-A5	395	1.17	5	12997
36	84	66b	MFM09-A5	398	1.17	5	13002
37	85	66c	MFM09-A5	401	1.17	5	13007
38	86	67a	MFM09-A5	405	1.17	5	13012
39	87	67b	MFM09-A5	408	1.17	5	13017
40	88	67c	MFM09-A5	411	1.17	5	13022
41	89	68a	MFM09-A5	415	1.17	5	13027
42	90	68b	MFM09-A5	418	1.17	5	13032
43	91	68c	MFM09-A5	421	1.17	5	13037
44	92	69a	MFM09-A5	425	1.17	5	13042
45	93	69b	MFM09-A5	428	1.17	5	13047
46	94	69c	MFM09-A5	431	1.17	5	13052
47	95	70a	MFM09-A5	435	1.17	5	13057
48	96	70b	MFM09-A5	438	1.17	5	13062
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No pollen preserved in this sample
This sample presents the Laacher See Tephra; no pollen prepared